

# MASSES OF HADRONS IN NUCLEI<sup>a</sup>

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We emphasize the central role played by the spectral function in the description of hadrons in matter and discuss the applicability of the quasiparticle concept to the propagation of hadrons in dense nuclear matter. Theoretical and experimental results relevant for the in-medium properties of vector mesons and kaons are briefly reviewed. We also present novel results for the  $\rho$  and  $\omega$  spectral functions in nuclear matter, deduced from a coupled channel analysis of pion-nucleon scattering data.

## 1 Introduction

The in-medium properties of hadrons is a topic of high current interest in the hadron and nuclear physics community. During the last few years the discussion has focused on kaons and light vector mesons because relevant experimental data has been available for these mesons. Indeed, in relativistic nucleus-nucleus collisions one finds enhancements in the spectrum of low-mass lepton pairs<sup>1,2</sup> and in the  $K^-$  multiplicity<sup>3</sup>. Presently several distinct theoretical interpretations of these findings exist. However, in almost all models that successfully reproduce the data, medium effects of some kind are invoked. Consequently, it seems likely that these data reflect nontrivial properties of dense hadron matter.

We begin by making some general remarks on quasiparticles in many-body systems, and then briefly recall the fairly well established properties of nucleons in nuclei as well as the expected characteristics of kaons and anti-kaons in nuclear matter. In the subsequent part we discuss theoretical models for the properties of vector mesons in matter and the experimental data on lepton-pair production in relativistic nucleus-nucleus collisions. Finally, we present a coupled channel approach to meson-nucleon scattering. In this approach, we fit the available meson-nucleon scattering data and extract the vector-meson-nucleon scattering amplitudes. With these amplitudes we then construct the

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<sup>a</sup>Plenary talk at BARYONS 98, Bonn, Germany, September 1998

vector-meson self energies in nuclear matter to leading order in density.

## 2 Quasiparticles

The quasiparticle concept, which was introduced by Landau in his theory of Fermi liquids<sup>4</sup>, has been very successfully applied to a rich variety of phenomena in liquid  $^3\text{He}$  and other low-temperature Fermi system<sup>5</sup>. Landau's theory was extended to nuclear physics by Migdal<sup>6</sup>. In Fermi liquid theory there is a one-to-one correspondence between the quasiparticle excitations of the interacting system and the single-particle excitations of the non-interacting system. In other words, a nucleon added to a nucleus turns into a quasiparticle (quasi-nucleon) when the interaction is turned on. In the interacting many-particle system, the single-particle strength is spread over many eigenstates of the Hamiltonian, i.e., the single-particle state is mixed with complicated many-particle states. Thus, the mass (or some other property) of a particle in an interacting many-body system, e.g. a hadron in a nucleus, is *a priori not* a well defined concept. Only if part of the single-particle strength is concentrated in a set of eigenstates that are close in energy, while the rest of the strength is spread over an almost uniform background, one can identify a unique quasiparticle. In that case one equates the in-medium properties of the particle with those of the corresponding quasiparticle.

The properties of the quasiparticle (mass, magnetic moment etc.) generally differ from those of the free particle. Moreover, because its strength is spread over several energy eigenstates, a quasiparticle normally has a width  $\Gamma_{QP}$  and consequently a finite lifetime  $\tau_{QP} = 1/\Gamma_{QP}$ , also when the corresponding particle is stable in vacuum. Thus, a quasiparticle typically corresponds to a peak with a finite width in the spectral function. We note that in mean-field approximations the quasiparticle width is neglected, i.e., the existence of a well defined quasiparticle is postulated. In general, the quasiparticle concept is useful for describing the response of the many-body system to probes, whose characteristic time scale is shorter than the quasiparticle lifetime. Whether this is the case for a given system, must be checked either by experiment or by calculation.

If the spectral function does not show a clear structure that can be identified with a quasiparticle peak, it obviously makes no sense to discuss the in-medium mass of the corresponding particle. In such a case the response of the many-body system is best described by means of the full spectral function. Detailed calculations show that this may in fact be the case for rho mesons<sup>7,8</sup> and negative kaons<sup>9</sup> in nuclear matter. In fig. 1 we show the  $K^-$  spectral function in nuclear matter of ref.<sup>9</sup>. Already at moderate densities and certain

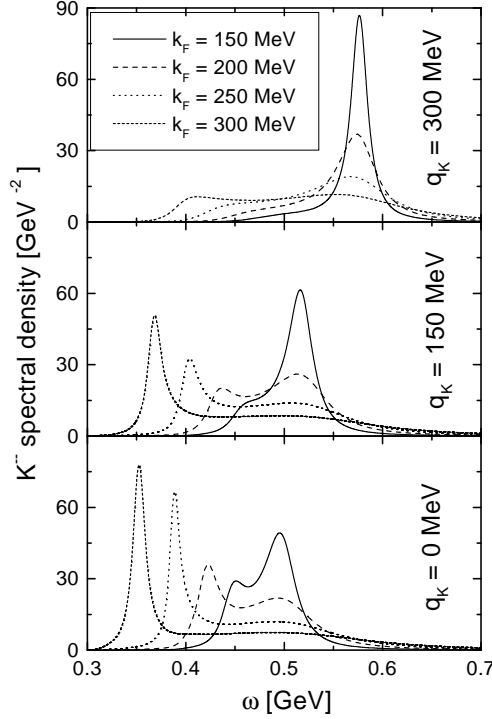


Figure 1: The  $K^-$  spectral function in nuclear matter at several densities and momenta from ref. <sup>9</sup>. The saturation density of nuclear matter,  $\rho_0 = 0.17 \text{ fm}^{-3}$  corresponds to  $k_F = 268 \text{ MeV}$ .

values of the 3-momentum, the kaon spectral density shows structures that are not described by a quasiparticle ansatz.

### 3 Hadrons in matter

The quasiparticles best known to nuclear physicist are nucleons in nuclei. Since the quasiparticles in Fermi systems are subject to the Pauli principle their widths vanish at the Fermi surface. Thus, a quasi-nucleon close to the Fermi surface has a long lifetime and consequently appears as an independent particle. This is essentially the reason for the success of independent particle models, like the shell model, in describing the structure of nuclei. The properties of the quasi-nucleons differ from those of free nucleons. An important property

is the nucleon effective mass  $m^*$ , defined by

$$\frac{p}{m^*} = \frac{d\varepsilon_p}{dp}, \quad (1)$$

which characterizes the non-locality of the average nuclear potential. One finds<sup>10,11</sup> that the nucleon effective mass close to the Fermi surface is almost equal to the free mass, while 10-20 MeV above or below the Fermi energy it is approximately 0.7  $m$ . Empirical constraints on the effective mass are obtained from the single-particle level density and phenomenological optical potentials for proton-nucleus scattering.

The in-medium properties of kaons have recently been the subject of intense discussions. In central heavy-ion collisions at sub-threshold energies, the KaoS collaboration at GSI<sup>3</sup> finds a substantial enhancement of the  $K^-$  yield per participant compared to proton-proton collisions. This effect can be interpreted in terms of a strong attractive medium modification of the  $K^-$ -spectrum, which facilitates the production of anti-kaons in the medium<sup>12,13</sup>. This scenario is consistent with calculations of kaon properties in nuclear matter<sup>14,15,16,9</sup>, which predict a weakly repulsive mass shift for  $K^+$  mesons and a very attractive, energy dependent potential for the  $K^-$  (see fig. 1). The predictions for kaon properties in nuclear matter are fairly robust at moderate densities since they are constrained by kaon-nucleon scattering data. We note, however, that the  $K^-$ -spectral density is subject to uncertainties since it probes the  $K^-$ -nucleon scattering process at sub-threshold kinematics which is not directly accessible in scattering experiments. Consequently, any prediction of the  $K^-$ -mass distribution is closely linked to the in-medium dynamics of the  $\Lambda(1405)$  resonance<sup>17,9</sup>, which plays a crucial role in  $K^-$ -nucleon scattering<sup>18</sup>.

The electromagnetic decay of vector mesons into  $e^+e^-$  and  $\mu^+\mu^-$  pairs makes them particularly well suited for exploring the conditions in dense and hot matter in nuclear collisions. The lepton pairs provide virtually undistorted information on the spectral distribution of the vector mesons in the medium. The low mass enhancement of lepton pairs found in ultra-relativistic nucleus-nucleus collisions by the CERES and HELIOS-3 collaborations<sup>1,2</sup> at CERN cannot be interpreted in terms of “standard” models, where the properties of the hadrons are not modified in the medium<sup>19</sup>.

Since the data show an enhancement compared to the results of such calculations at invariant masses below the  $\rho/\omega$  peak, a natural interpretation of the enhancement could be that the in-medium masses of the light vector mesons are strongly reduced in dense/hot hadron matter. Indeed, Li, Ko and Brown find very good agreement with the data in the universal scaling scenario, where the  $\rho$  and  $\omega$  masses decrease with increasing baryon density<sup>20</sup>. This scenario

is based on the universal scaling approach of Brown and Rho<sup>21</sup>, where the masses of all hadrons, except for pseudo-scalar mesons, drop in proportion to the quark condensate.

An alternative interpretation of the low-mass enhancement of lepton pairs, based on effective hadronic models for the vector-meson self energy in matter, has been explored by Rapp, Chanfray and Wambach<sup>22</sup>. In this approach, the starting point is an effective hadron Lagrangian, whose parameters ideally are determined by hadronic interactions in vacuum. The vector-meson properties in matter are then computed by evaluating the corresponding self energy using standard many-body techniques. Several groups have done calculations along these lines, with qualitatively similar results. One finds a strong enhancement of the in-medium width of the  $\rho$  meson due to the strong interaction of the pion cloud with the surrounding nucleons<sup>23,24,25,26,7</sup>, as well as a momentum dependence of the  $\rho$ -meson spectral function due to s-channel baryon resonances<sup>27,7</sup>. Both the enhanced width and the momentum dependence leads to a shift of  $\rho$ -meson strength to smaller invariant masses. When these effects are implemented in a simulation of heavy-ion collisions, Rapp *et al.* find good agreement with the data<sup>22</sup>.

In the following section we present a recent calculation in an effective hadronic model. This calculation is a first attempt to include, in a systematic fashion, constraints from meson-nucleon scattering data in the energy regime relevant for the properties of vector mesons in nuclear matter ( $\sqrt{s} \simeq 1.7$  GeV). Previous calculations were based on effective interactions adjusted to low-energy data only. These necessarily involve extrapolations over a wide range in energy, which introduce a strong model dependence<sup>28</sup> and consequently should be avoided whenever possible.

#### 4 Meson-nucleon scattering

In this section we describe a relativistic and unitary coupled channel approach to meson-nucleon scattering<sup>29</sup>. The following channels are included:  $\pi N$ ,  $\rho N$ ,  $\omega N$ ,  $\pi\Delta$  and  $\eta N$ . Our goal is to determine the vector-meson-nucleon scattering amplitude since it determines the self energy of a vector-meson in nuclear matter to leading order in density. In this work we focus on vector mesons with small or zero 3-momentum with respect to the nuclear medium. Therefore it is sufficient to consider only s-wave scattering in the  $\rho N$  and  $\omega N$  channels. This implies that in the  $\pi N$  and  $\pi\Delta$  channels we need only s- and d-waves. In particular, we consider the  $S_{11}$ ,  $S_{31}$ ,  $D_{13}$  and  $D_{33}$  partial waves of  $\pi N$  scattering. Furthermore, we consider the pion-induced production of  $\eta$ ,  $\omega$  and  $\rho$  mesons off nucleons.

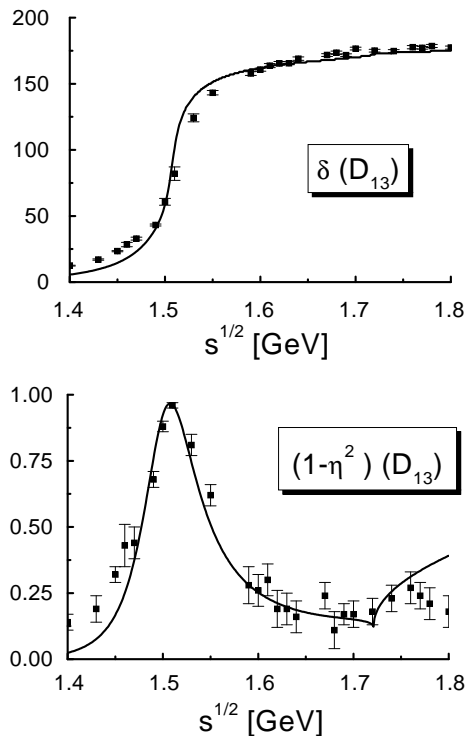


Figure 2: The  $\pi N$  scattering phase shifts and inelasticity in the  $D_{13}$  channel. The line shows the best fit, while the data points are those of the analysis of Arndt *et al.* <sup>30</sup>.

We recall that at small densities the spectral function of a vector meson in nuclear matter with energy  $\omega$  and zero momentum probes the vector-meson nucleon scattering process at  $\sqrt{s} \sim m_N + \omega$ . In order to learn something about the momentum dependence of the vector-meson self energy, vector-meson–nucleon scattering also in higher partial waves would have to be considered.

In accordance with the ideas outlined above only data in the relevant kinematical range will be used in the analysis. The threshold for vector-meson production off a nucleon is at  $\sqrt{s} \simeq 1.7$  GeV. We fit the data in the energy range  $1.45 \text{ GeV} \leq \sqrt{s} \leq 1.8 \text{ GeV}$ , using an effective Lagrangian with local 4-point meson-meson–baryon-baryon interactions. For details the reader is referred to ref. <sup>29</sup>.

In fig. 2 our fit to the  $\pi N$  scattering data is illustrated by the  $D_{13}$  channel.

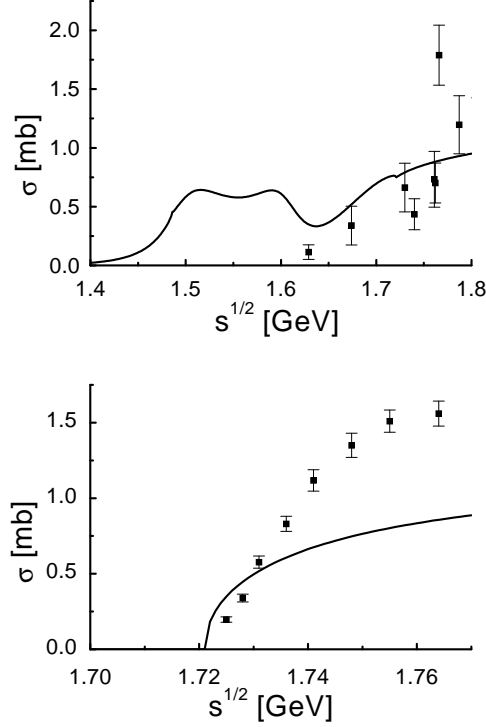


Figure 3: The cross sections for the reactions  $\pi^- p \rightarrow \rho^0 n$  (top) and  $\pi^- p \rightarrow \omega n$  (bottom). The data are from ref. <sup>31,32</sup> and ref. <sup>33</sup>, respectively.

In the remaining channels the fit is of similar quality. Furthermore, in fig. 3 the cross sections for the reactions  $\pi^- p \rightarrow \rho^0 n$  and  $\pi^- p \rightarrow \omega n$  are shown. The agreement with the data is satisfactory close to threshold, but the energy dependence is not reproduced. This may be due to the coupling to channels, like the  $K - \Sigma$  channel, as well as higher partial waves, not yet included in our scheme.

The bumps in the  $\rho$ -production cross section at  $\sqrt{s}$  below 1.6 GeV are due to the coupling to resonances below the threshold, like the  $N^*(1520)$ . This indicates that these resonances may play an important role in the  $\rho$ -nucleon dynamics, in agreement with the results of Manley and Saleski<sup>34</sup>. However, the strength of the coupling is uncertain, due to the ambiguity in the  $\rho$ -production cross section close to threshold. We find that also the  $\omega$  meson couples strongly

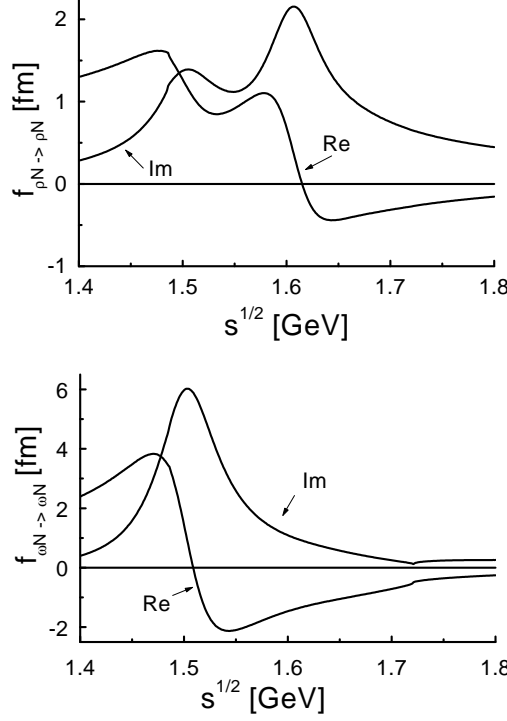


Figure 4: The  $\rho N$  and  $\omega N$  scattering amplitudes, averaged over spin and isospin.

to these resonances. The pion-induced  $\eta$ -production cross section (not shown) is well described up to  $\sqrt{s} \simeq 1.65$  GeV. At higher energies presumably higher partial waves, presently not included in our model, become important.

The resulting  $\rho$ - and  $\omega$ -nucleon scattering amplitudes are shown in fig. 4. The  $\rho - N$  and  $\omega - N$  scattering lengths, defined by  $a_{VN} = f_{VN}(\sqrt{s} = m_N + m_V)$ , are  $a_{\rho N} = (-0.3 + 0.7i)$  fm and  $a_{\omega N} = (-0.5 + 0.1i)$  fm. To lowest order in density, this corresponds to the following in-medium modifications of masses and widths at nuclear matter density:  $\Delta m_\rho \simeq 30$  MeV,  $\Delta m_\omega \simeq 50$  MeV,  $\Delta \Gamma_\rho \simeq 140$  MeV and  $\Delta \Gamma_\omega \simeq 20$  MeV. However, as we show in the next section, the coupling of the vector mesons to baryon resonances below threshold, which is reflected in the strong energy dependence of the amplitudes, cannot be neglected.



## 5 Vector mesons in nuclear matter

In this section we present results for the in-medium propagators of the  $\rho$ - and  $\omega$ -mesons at rest, obtained with the scattering amplitudes presented in section 4, to leading order in density. The low-density theorem states that the self energy,  $\Delta m_V^2(\omega)$ , of a vector meson  $V$  in nuclear matter is given by<sup>35</sup>

$$\Delta m_V^2(\omega) = -4\pi(1 + \frac{\omega}{m_N})f_{VN}(\sqrt{s} = m_N + \omega)\rho_N + \dots, \quad (2)$$

where  $\omega$  is the energy of the vector meson,  $m_N$  the nucleon mass,  $\rho_N$  the nucleon density and  $f_{VN}$  denotes the  $VN$  s-wave scattering amplitude averaged over spin and isospin. In fig. 5 we show the resulting propagators at the saturation density of nuclear matter,  $\rho_0 = 0.17 \text{ fm}^{-3}$ . For the  $\rho$  meson we note a strong enhancement of the width, and a downward shift in energy, due to the mixing with the baryon resonances at  $\sqrt{s} = 1.5 - 1.6 \text{ GeV}$ . Thus, our results lends support to the dynamical scenario discussed in ref.<sup>36</sup>. The center-of-gravity of the spectral function is shifted down in energy by  $\simeq 10 \%$ .

The in-medium propagator of the  $\omega$  meson exhibits two distinct quasi-particles, an  $\omega$  like mode, which is shifted up somewhat in energy, and a resonance-hole like mode at low energies. The low-lying mode carries about 20 % on the energy-weighted sum rule. Again, the center-of-gravity is shifted down by  $\simeq 10 \%$ . However, we stress that the structure of the in-medium  $\omega$  spectral function clearly cannot be characterized by this number alone.

We expect that the results obtained with only the leading term in the low-density expansion are qualitatively correct at normal nuclear matter density. However, on a quantitative level, the spectral functions may change when higher order terms in the density expansion, induced e.g. by p-wave vector-meson–nucleon interactions, are included.

## 6 Conclusions

We reviewed general aspects of quasiparticles in many-body systems and emphasized the importance of the spectral function for the discussion of hadron properties in matter. Furthermore, recent theoretical and experimental developments relevant for the study of kaons and vector mesons in a hadronic environment were presented.

We also reported on a relativistic and unitary, coupled channel approach to meson-nucleon scattering. The parameters of the effective interaction are determined by fitting elastic pion-nucleon scattering and pion-induced meson production data in the relevant energy regime. We obtain a model for the  $\rho$ - and  $\omega$ -N scattering amplitudes, which allows us to compute the vector-meson

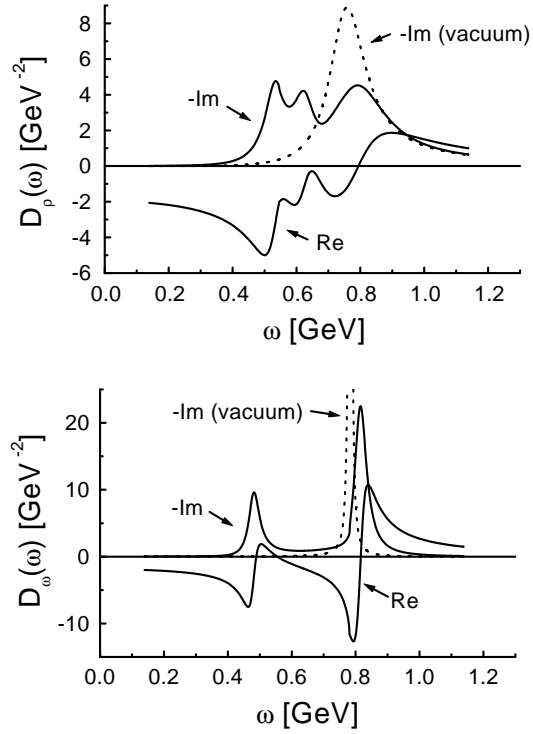


Figure 5: Real and imaginary parts of the  $\rho$  and  $\omega$  propagators in nuclear matter at  $\rho_0$ , compared to the imaginary parts in vacuum.

self energies in nuclear matter to leading order in density. In this approach we avoid the extrapolation from low-energy data, which is a weak point in previous calculations.

A prominent feature of the scattering amplitudes is the strong coupling to baryon resonances below threshold. This leads to two characteristic features of the vector-meson spectral functions, namely repulsive scattering lengths and a spreading of the vector-meson strength to states at low energy. The latter is, as discussed above, qualitatively what seems to be required by the heavy-ion data. Clearly, complementary experiments with e.g. photon and pion induced vector meson production off nuclei would be extremely useful for exploring the in-medium properties of these mesons in more detail.

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